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Chapter Thirty-three

BRIDGE DECK DRAINAGE

33-1.0 INTRODUCTION

The objective of this Chapter is to present a sound, economic and low-maintenance design for bridge deck and bridge end drainage facilities. The detrimental effects of runoff emphasize the importance of removing water from the bridge deck as quickly as practical. This highlights the need for an efficient drainage system that always works properly. Proper design provides benefits for traffic safety, maintenance, structural integrity and aesthetics.

33-1.01 Scope

This Chapter provides guidelines and procedures for designing bridge deck drainage systems, including illustrative and practical examples. It incorporates hydraulic capacity, traffic safety, structural integrity and practical maintenance. System hardware components, such as inlets, pipes and downspouts, are described. It provides guidance for selecting a design gutter spread and flood frequency and a design methodology for inlet spacing including example problems.

33-1.02 Objectives

Several objectives are important in developing a design that will control the spread of water into traffic lanes, will function properly with a minimum of maintenance, and will not interfere with the architectural beauty or structural integrity of the bridge. These are discussed in the following sections.

33-1.02(01) Minimization of Maintenance

Many bridges will not require any drainage structures. This is ideal because of the high maintenance normally required to maintain deck drains and other types of inlets free from debris discarded from vehicles and sand deposited during winter maintenance activities. A clogged deck drain can cause more encroachment of runoff onto the shoulder or travel lane than no drainage structure. Bridge deck drains may be necessary in addition to riprap turnouts to capture runoff from the bridge and convey it to an appropriate outlet.

33-1.02(02) Minimization of Spread

As water accumulates and spreads across the width of the gutter and into the travel lane, it can reduce service levels and cause safety problems. Where inlets are required, they must be adequately sized and spaced to remove runoff from the bridge deck before it encroaches onto the traveled way to the limit of the design spread.

This Chapter presents a procedure to determine the maximum length of deck allowable without exceeding the design spread. See Chapter Thirty-six for more information.

33-1.02(03) Avoidance of Hydroplaning

Precipitation produces sheet flow on pavements and gutter flow. If sheet flow or spread has sufficient depth, the tires can separate from the pavement surface and produce hydroplaning. To reduce this risk, the drainage system must be designed to prevent the accumulation of significant depths of water.

33-1.02(04) Reduction of Icing Potential on Deck

Bridge decks are usually the first segment of a highway to become icy in cold weather. Adequate deck drainage through use of minimum grades and cross slopes is essential to prevent the accumulation and spreading of icy spots. Icy bridge decks caused by frost are difficult to prevent except by surface texture and maintenance practices. Proper signing to warn the motoring public of the potential of ice on bridges may be appropriate.

33-1.02(05) Integration into Structural Dimensions

The deck drainage system must conform to the structural requirements of the bridge. Drainage details affect structural design. For example, inlets for reinforced concrete bridge decks must fit within the reinforcing bar design. If deck drainage is not needed, structural design is free of inlet details. In addition, the drainage system should prevent water, road salt and other corrosives from contacting the structural components.

33-1.02(06) Aesthetics

A pipe system conveying water from deck inlets to natural ground can be affixed to exterior surfaces of a bridge. However, encasing the piping in structural members may not be advisable because of potential freezing damage. Pipes affixed to exterior surfaces of structures, running at odd angles, can present an unpleasant silhouette and detract from the bridge's architectural aesthetics. To avoid this, pipes can be located in slots up the back of the columns or can be hidden behind decorative pilasters.

33-1.03 Concept Definitions

The following are definitions of concepts which are important in bridge deck drainage analysis and design.

1. Cleanout plug. A removable plug in the piping system that provides access to a run of piping for cleaning. It is typically located near bends and Y-shaped intersections.

2. Cross Slope. The slope of the pavement cross section from the curb to the crown.

3. Drop Inlet. A drain that is used away from a bridge or at bridge ends. It is usually larger than an inlet chamber and is set in earth in the subgrade or shoulder of an approach embankment. It has a horizontal or near-horizontal opening.

4. Drain. A receptacle that receives and conveys water.

5. Drainage System. The entire arrangement of grates, drains, inlet chambers, pipes, gutters, ditches, outfalls and energy dissipators necessary to collect water and convey it to a disposal point.

6. Grate. The ribbed or perforated cover of an inlet chamber that admits water and supports traffic loads. Typically, grates are removable to allow access for maintenance.

7. Inlet Chamber. The typically small cast-iron, welded steel, or formed concrete compartment that is beneath a grate. Although usually set into the bridge deck, it is sometimes only an open hole in the deck.

8. Outlet Pipe. The pipe that leads the water away from an inlet chamber or drop inlet.

9. Runoff, Drainage. Any liquid that can run off the roadway surface. Although the liquid is generally water, it includes any other liquids and dissolved solids that can make their way into the drainage system.

10. Scupper. A small opening in the curb or barrier through which water can flow from the bridge deck. The term is nautical and by analogy relates bridge deck drains to openings in the sides of ships at deck level to allow water to exit.

11. Spread. The top of water measured laterally from the bridge curb.

12. Storm Drain. A beneath-the-bridge and underground piping system that may connect to a municipal storm drain system or may be a separate collection system for highway and bridge drainage.

33-2.0 SYSTEM COMPONENTS

The bridge deck drainage system includes the bridge deck itself, bridge gutters, inlets, pipes, and downspouts. The details of this system are typically designed by the bridge engineer and coordinated with the Hydraulics Unit. Coordination of efforts is essential in designing the various components of the system to meet the objectives described in Section 33-1.0.

33-2.01 System Requirements

The primary requirement of the drainage system is to remove rainfall-generated runoff from the bridge deck before it collects and spreads in the gutter to encroach onto the traveled way and exceed the limit of a design spread. To meet this objective, the drainage system must meet other design criteria, as presented below.

33-2.01(01) Structural Considerations

The primary structural considerations in bridge deck drainage system design are as follows:

1. Inlet sizing and placement must be compatible with the structural reinforcement and components of a bridge.

2. The drainage system should be designed to deter flow from contacting vulnerable structural members and to minimize the potential of eroding embankments.

Structural and hydraulic engineers should work together to design a system that has the necessary hydraulic capacity and is compatible with structural elements. To avoid corrosion and erosion, the design must include proper placement of outfalls, including prevention of flow from splashing or being blown back onto support members. In addition, water should be prevented from running down the joint between the pavement and the bridge and thereby undermining an abutment or wingwall.

33-2.01(02) Decks and Gutters

The bridge deck and gutters are surfaces that initially receive precipitation. If grades, superelevations, and cross slopes are properly designed, water and debris are efficiently conveyed to the inlets or riprap turnouts. Bridge deck designs with zero grades or in sag vertical curves have poor hydraulics and may cause ponded water and hydroplaning problems. Superelevation transitions through a zero grade may cause water and ice problems as well. The cross slope is typically 2% on tangent sections. Flat gradients and sag vertical curves are not normally allowed for bridges on new alignment. The desirable longitudinal grade for bridge deck drainage is 0.5% or greater. Flatter grades will be tolerated where it is not physically or economically desirable to meet the above criteria.

33-2.01(03) Drainage Appurtenances

These include inlets, grates, pipes and downspouts. From the deck and gutters, water and debris flow to the inlets, through pipes and downspouts, and finally to the outfall. Various grate and inlet box designs are available to discourage clogging. Collector pipes and downspouts with smooth Y-connections and bends help prevent clogging in mid-system. T-connections are discouraged because of their propensity to plug. Collector pipes need sufficient slope (2.0%) to sustain self-cleaning velocities. Cleanout plugs located near curves and Y-connections should be included to provide access to the pipe to facilitate cleaning. Storm drainage systems beneath bridges may be necessary to transport runoff to side ditch, storm drain or storm water detention facilities.

33-2.01(04) Riprap Turnouts

See Figure 33-2A, Slope Wall, Riprap and Sodding Limits for Grade Separation Structures, for grade separations and Figures 17-4 I and 17-4J for stream crossings.

33-2.01(05) Bridge End Collectors on Curbed Roadways

On curbed roadways drainage inlets placed at the ends of bridges are essential for proper drainage. Grate inlets, curb opening inlets or combination inlets, may be used for bridge ends. The hydraulic characteristics of the inlets should be considered in selecting the type. Inlets placed on the upslope end of the bridge should be designed to collect all of the runoff upslope of the bridge. This will prevent the bridge deck drains and inlets from being overtaxed from runoff entering onto the bridge from the approaches. Collectors at the downslope end of the bridge should be designed to collect all of the flow not intercepted by the bridge inlets. A conservative design approach is to assume that 50% of the inlets on the bridge are plugged and to size the end collectors accordingly. If there are no bridge inlets, downslope inlets should be designed to intercept all of the bridge drainage. From the inlet structure, there must be either a pipe, paved channel or trough to transport the water down the face of the embankment.

33-2.02 Bridge Deck Inlets

33-2.02(01) Types

Bridge deck inlets must remove water from a bridge deck within the limits of allowable spread. Considering hydraulics, inlets should be large and widely separated and, considering structures, inlets should be avoided or be as small and as few as practical. This Section presents typical inlet designs used by INDOT and discusses the factors that affect inlet interception capacity. In addition, this Section discusses design features to help prevent clogging, and it provides guidance for determining inlet locations. The following inlets are currently in use.

1. Grate A. This grate fits on Roadway Drain Type SQ. It is a parallel bar grate and the most hydraulically efficient of the grates in use. The grate is 480 mm square. Because the openings are 25-mm wide, the grate is not considered bicycle safe when placed with bars parallel to the direction of traffic. However, it is feasible to use this grate where bicycle traffic is allowed on the bridge if the bars are placed perpendicular to the direction of travel. Note on Figure 33-5C, Grate Inlet Frontal Flow Interception Efficiency, that this perpendicular arrangement may substantially reduce the hydraulic capacity of the grate. The outlet fitting is 150-mm round pipe.

2. Grate D. This grate fits on Roadway Drain Type OS. This is a Type C grate with parallel bars but has two transverse bars which prevent bicycle wheels from dropping into the inlet; therefore, it is considered bicycle safe. The transverse bars reduce the hydraulic

capacity of the grate. The grate dimensions are 480 mm wide by 510 mm long. The outlet fitting is 150-mm round pipe.

3. Slab Bridge Floor Drain Detail. These deck drains are designed for reinforced concrete slab bridges only. The drain is a 150-mm PVC pipe set into the deck. These small deck drains have limited hydraulic capacity; therefore, the spacing will be much closer than the above grates. The standard spacing is approximately 1800 mm. A 15-mm depression, which extends 300 mm transversely from the face of the curb, increases the capacity slightly.

4. Curved Vane Grate. On curbed roadways where inlets are located off the bridge deck, use the INDOT curved vane grate.

5. Concrete Barrier Rails (Scuppers). INDOT prohibits the use of scuppers through concrete barrier rails except on local public agency bridges.

33-2.02(02) Interception Capacity and Efficiency

Inlet interception capacity is the flow intercepted by a bridge deck inlet under a given set of conditions. The efficiency of an inlet is the percent of total flow that the inlet will intercept. The efficiency of an inlet varies with cross slope, longitudinal slope, total gutter flow and, to a lesser extent, pavement roughness. Efficiency, E, is defined as follows:

$$E = \frac{Q_i}{Q} \qquad \text{(Equation 33-2.1)}$$

Where: Q = Total gutter flow, m^3/s
Q_i = Intercepted flow, m^3/s

The intercepted flow consists of frontal flow entering the inlet parallel to the gutter and flow entering from the side of the inlet. For small, rectangular inlets, side flow is assumed to be small. The ratio of side flow intercepted to total side flow, R_s, is defined by the following equation:

$$R_S = \frac{12.08}{12.08 + \left(\frac{V^{1.8}}{S_X L_g^{2.3}}\right)} \qquad \text{(Equation 33-2.2)}$$

Where: L_g = Length of the inlet parallel to the flow, m
V = Average velocity in the gutter, m/s
S_X = Pavement cross slope, m/m

Because the side flow is small compared to the total flow, the inclusion of side flow is at the discretion of the designer. Equation 33-2.3 describes the ratio of frontal flow to total gutter flow:

$$E_O = 1 - \left[1 - \left(\frac{W}{T}\right)\right]^{2.67} \qquad \text{(Equation 33-2.3)}$$

Where: W = Width of the inlet, m
T = Width of the design spread, m

Figure 33-5B presents a solution to Equation 33-2.3. The fraction of frontal flow that actually enters the inlet can be expressed as:

$$R_f = 1 - 0.3(V - V_O)^4 \qquad \text{(Equation 33-2.4)}$$

Where: R_f = Frontal flow capture fraction
V = Gutter velocity, m/s
V_O = Grate splash-over velocity, m/s (Figure 35-5C)

Note: See Figure 33-5C, Grate Inlet Frontal Flow Interception Efficiency, for a nomograph solution.

33-2.03 Inlet Locations

33-2.03(01) Factors

The deck spread criteria and geometric controls will determine the optimal hydraulic location of inlets. See Section 33-4.0. However, structural constraints, maintenance considerations and other factors will influence the actual location of inlets. For pavements on grade, design spread will determine the distance between grates. The designer should exercise special care to intercept gutter flow on horizontal curves or within superelevation transitions to minimize water flow across the bridge deck.

33-2.03(02) Spacing

Determining the maximum spacing between inlets is straightforward if the drainage area consists of pavement only or has reasonably uniform runoff characteristics and is regularly shaped. This assumes that the time of concentration (t_C) is the same for all evenly spaced inlets. See Section 33-5.0 for inlet spacing calculations.

33-2.03(03) Sag Vertical Curves

Where significant ponding can occur in sag vertical curves, good practice is to place flanking inlets on each side of the inlet at the low point of the sag. The flanking inlets should be placed so that they will limit spread on low gradient approaches to the level point and act in relief of the inlet at the low point if it should become clogged or if the design storm is exceeded. See Section 36-10.0.

33-2.03(04) Minimum Number/Location

The following applies to standard inlet location.

1. Structures with Curbs.

    a. Structures on grade with structure lengths less than 50 m or structures with crest vertical curves on bridges and structure lengths less than 75 m˜ no inlets are required; however, hydraulic calculations for deck drains are required.

    b. For structures on grade, provide roadway drains at ends of structure at the low end and a riprap turnout at the end of the rail transition.

    c. For structures on crest vertical curves, provide a round roadway drain on all four corners of the bridge and provide riprap turnouts at the end of the rail transitions.

    d. For structures on sag vertical curves, a minimum of two roadway inlets are required.

2. Structures Without Curbs. No inlets or riprap turnouts are required.

3. Grade Separation Structures. For grade separation structures requiring deck drainage at the ends of the bridge, deck drains shall discharge into inlets located in the berm or on the slopewall under the bridge as shown on the INDOT *Standard Drawings*.

33-2.03(05) Coordination with Deck Reinforcement

Inlet locations must be considered in the design and layout of the reinforcement spacing within the deck and must not promote corrosion of the structural members. Additional reinforcement should be provided around the deck drain to maintain the continuity of the deck reinforcement.

33-2.03(06) Maintenance

Maintenance is an important factor in successful deck drainage. An inlet should be placed where it can be serviced easily and safely by a maintenance crew. A difficult-to-reach inlet will be neglected and inevitably become plugged. Inlets placed in traffic lanes may plug due to vehicles forcing debris into an inlet.

<u>33-2.04 Underdeck Collectors and Discharge System</u>

33-2.04(01) Design

The following applies to the design of the underdeck drainage system.

1. <u>General</u>. Bridge drainage pipes beneath decks are generally sized larger than needed for hydraulic purposes to facilitate maintenance. The minimum pipe size should be 150 mm. The inlet conditions will control the flow capacity. Entrances, bends and junctions in the underdeck pipe system provide opportunities for debris to snag and collect. Provide smooth transitions and smooth interior surfaces. Avoid sharp bends, corner joints and bevel joints.

2. <u>Velocity</u>. A recommended minimum velocity for storm drains is 0.8 m/s. Because vertical fall for pipes beneath bridges is typically available, an 8% slope is a good minimum to transport sand and silt through the pipe at over 0.8 m/s.

3. <u>Standard Design</u>. The standard design for the cast-iron roadway drains used by the Department is presented in the INDOT *Standard Drawings*.

4. <u>Alternative Designs</u>. Figure 33-2B, Ratio of Frontal Flow to Total Gutter Flow (Rectangular Inlets), illustrates two typical alternatives for drains. Figure 33-2B(a) shows a traditional arrangement including a short overhang and a steel beam, which permits the drain pipe to be located internally with reference to the external beam. Figure

33-2B(b) shows another arrangement including a large overhang and a bulb-tee beam, which locates the drain pipe to the outside. This is aesthetically less pleasant, emphasizing the desirability of keeping the number of drains to a minimum.

5. Drain Location (Exterior Beam). Drainage castings should be positioned such that the outlet pipe is located inside the exterior beam, if practical. See Figure 33-2B(a). If not, the casting type and position should be selected to locate the drainage pipe as close as practical to the exterior beam. The plans should illustrate the drain location, positioning and attachment details.

6. Longitudinal Pipes (Closed Drainage). These pipes must not extend below the superstructure. The minimum slope is 1% for longitudinal pipes between drains or from a drain to the point of discharge.

7. Overpasses. Open deck drains should not be located over a roadway, sidewalks or railroads. If drains must be located in this area, a closed drainage system shall be provided.

8. Pipe Materials. The pipes in the underdeck collector and discharge system will be paid for in meters of PVC pipe or as a lump-sum item of Steel Drain Pipe, standard weight.

   If cast iron drain pipe is used for the connection to the deck drain casting, it will be billed as C.I.Pipe, 150-mm diameter (extra heavy), (____#____), @ (____length____) m @ 26.78 kg/m = (____weight____) kg.

33-2.04(02) Free-Fall

The following applies to the free-fall, where used beneath a bridge.

1. The downspouts should be extended 150 mm below the beam soffit. Downspouts should be placed approximately 3 m from the face of substructure units, unless a closed drainage system is used. In no case may downspouts interfere with the required horizontal or vertical clearances. Note that pipe systems designed to bring water down to ground level may become clogged by debris and ice and should only be used as the last option.

2. They should not discharge water where it can easily blow over and run down a column or pier.

3. Water should not be discharged openly over any traveled way (either vehicular, railroad or pedestrian), unpaved embankment or unprotected ground where it might cause erosion

or undermine any structural element. In such cases, energy dissipators and/or riprap should be provided to prevent erosion.

4. A free fall exceeding about 7.5 m will sufficiently disperse the falling water so that no erosion damage will occur beneath the bridge. In cases where the water freefalls onto riprap or flowing water, lesser freefalls will be permissible.

33-2.04(03) Cleanouts

Cleanouts for maintenance access should be provided at key points within the system to facilitate the removal of obstructions. Maintenance downspouts should be located so the maintenance crew can access them from underneath the bridge and preferably from the ground. Attaining the most convenient arrangement is important because cleanouts that are inaccessible or difficult to reach simply will not be cleaned.

33-3.0 CALCULATION OF RUNOFF

33-3.01 Rational Method

The conventional method for estimating runoff for bridge deck drainage is the Rational Method. This hydrologic method is discussed in detail in Chapter Twenty-nine. This Section briefly discusses the Rational Method as it pertains to bridge deck drainage.

The Rational formula is as follows:

$$Q = 0.00278\,CiA \qquad \text{(Equation 33-3.1)}$$

Where:

Q = The peak runoff rate, m^3

C = A dimensionless runoff coefficient that represents characteristics of the drainage area. Typically, $C = 0.9$ for bridge decks.

i = Rainfall intensity, mm/hr

A = Drainage area, hectares

33-3.02 Rainfall Intensity

For bridge decks, the determination of a design rainfall intensity for use in the Rational Method can be based on the following:

1. the time of concentration, which is a function of the design spread;
2. the specific intensity at which driver vision will be impaired; or
3. the condition for which hydroplaning will occur.

The most common source of rainfall intensity data is from Intensity-Duration-Frequency (IDF) curves which can be plotted for the location in question. Other sources of rainfall intensity data are available and will be discussed in the following.

The design rainfall intensity can be obtained from IDF Curves for the exact location (latitude and longitude) of the project. This is readily available from the HYDRO module of the computer program HYDRAIN. Regional IDF curves for use throughout Indiana are included in Chapter Twenty-nine. Generally, the rainfall intensity obtained from the IDF curve is a conservative design value when compared with values obtained from hydroplaning or driver vision criteria. Because these latter criteria involve variable factors, such as tire tread wear and driver behavior, one approach is to use the IDF curve as the governing criteria for selecting rainfall intensity and then compare that intensity to the other two criteria. The most conservative rainfall intensity value should be used.

For bridge deck drainage, the design flood for determining the spacing/location of inlets is based on a 10-year return period except for freeways which are based on a 50-year return period. Rainfall intensities from 125 mm/hr to 165 mm/hr for times of concentration of 5 to 10 minutes during a 10-year frequency storm are not unusual.

33-3.03 Time of Concentration

HEC 12 *Drainage of Highway Pavements* assumes that inlets are independent drainage elements that collect runoff from their small contributing drainage areas. This assumption yields a conservative and constant time of concentration for deck inlets and scuppers equally spaced and equals the time of concentration to the first inlet.

The time of concentration for bridge deck inlets consists of two components˜ overland flow time and gutter flow time. The overland flow is sheet flow from the deck high point to the gutter. Gutter flow time is the time of flow in the gutter. The following presents equations for determining times of concentration for both overland flow, t_O, and gutter flow, t_g.

$$t_O = \frac{k_w (l_O n)^{0.6}}{(Ci)^{0.4}(S)^{0.3}} \qquad t_O = 6.92\frac{(W_P n)^{0.6}}{(Ci)^{0.4}(S)^{0.3}} \qquad \text{(Equation 33-3.2)}$$

33-3.03(01) Overland Flow Time of Concentration

Where: t_O = Time of overland flow, minutes
l_O = W_p = Overland, flow length, m
n = Manning's roughness coefficient
C = Runoff coefficient
i = Rainfall intensity, mm/hr
S = Average slope of the overland area
k_W = 6.92, a constant

33-3.03(02) Gutter Flow Time of Concentration

$$t_g = k_g\left(\frac{S_x T^2}{Ci\,W_P}\right) \qquad \text{(Equation 33-3.3)}$$

Where: t_g = Time of gutter flow, minutes
S_X = Cross slope of gutter, m/m
T = Spread, m
C = Runoff coefficient
i = Rainfall intensity, mm/hr
W_P = Width of pavement contributing runoff, m
k_g = 40 333, a constant

Figure 33-3A illustrates the cross section elements which apply to Equation 33-3.3.

33-3.03(03) Total Time of Concentration

The total time of concentration, t_C, is the sum of t_O and t_g.

33-4.0 FLOW IN GUTTERS

A bridge deck gutter is defined as the section of pavement adjacent to the curb or parapet that conveys water during a storm runoff event. It may include a portion or all of a travel lane.

Gutter cross sections usually have a triangular shape with the curb forming the near-vertical leg of the triangle. Bridge deck gutters typically have straight cross slopes.

Chapter Thirty-six discusses gutter flow in detail relative to pavement drainage. This Section briefly discusses gutter flow as it pertains to bridge deck drainage.

For bridge decks, a modification of the Manning equation is necessary for use in computing flow in triangular channels because the hydraulic radius in the equation does not adequately describe the gutter cross section, especially where the top width of the water surface may be more than 40 times the depth at the curb. The resulting equation is:

$$Q = \left(\frac{k_g}{n}\right) S_x^{1.67} S^{0.5} T^{2.67} \qquad \text{(Equation 33-4.1)}$$

Where:

Q	=	Flow rate, m^3/s
k_g	=	0.38, a constant
T	=	Width of flow (spread), m
S_X	=	Cross slope, m/m
S	=	Longitudinal slope, m/m
n	=	Manning's roughness coefficient

Figure 33-4A illustrates the cross section which applies to Equation 33-4.1.

Chapter Thirty-six presents INDOT criteria for allowable water spread (T) on bridge decks, which is typically as follows:

1. Freeways. Edge of traveled way for Q_{50}.
2. Non-Freeways. 1.2 m into outside travel lane for Q_{10}.
2. Ramps. 2.4 m of roadway must remain clear of water for Q_{10}.

Gutter velocity is determined by dividing the gutter flow equation by the cross-sectional area of the gutter. The resulting relation is:

$$V = \left(\frac{2k_g}{n}\right) S^{0.5} S_x^{0.67} T^{0.67} \qquad \text{(Equation 33-4.2)}$$

Where: V = Gutter velocity, m/s

33-5.0 INLET SPACING

Chapter Thirty-six discusses inlet spacing in detail for pavements. This Section presents methods specifically for determining inlet spacing for constant-slope bridges, flat bridges and vertical curve bridges. Example problems are also included.

33-5.01 Constant-Grade Bridges

33-5.01(01) Procedure

An IDF curve for the appropriate location will be necessary. HYDRO can be used to generate an IDF curve for a known latitude and longitude, or the designer may use the closest regional IDF curve in Chapter Twenty-nine. The designer must select a return period (typically ten years) and design spread (see Section 33-4.0 and Chapter Thirty-six). If the bridge slope is nearly flat (less than about 0.3%), then the procedures for flat bridges should also be followed as a check. The general hydraulic procedure is to start at the high end of the bridge and work downslope from inlet to inlet. Use the following procedure:

1. Step 1. An iterative process is necessary to determine a rainfall intensity, i, because this value is necessary to solve both Equations 33-3.2 and 33-3.3. Assume a value of i and solve for overland time of concentration using Equation 33-3.2 and gutter flow time of concentration using Equation 33-3.3. Add the times together for total time. If less than five minutes, use five minutes. Compare with the assumed value and repeat the process if not sufficiently close. Select a design rainfall intensity from the IDF data.

2. Step 2. Find the flow on the deck, Q, at design spread, T, using Equation 33-4.1.

3. Step 3. Starting at the high end of the bridge, the inlet spacing can be computed using Equation 33-5.1 as follows:

$$L_c = \left[\frac{(3.63 \text{ x } 10^6)Q}{Ci\,W_P}\right](E) \qquad \text{(Equation 33-5.1)}$$

Where: L_C = Distance to the first inlet or between inlets, m

i = Design rainfall intensity, mm/hr (Step 1)

Q = Gutter flow, m^3/s (Step 2)

C = Rational runoff coefficient

W_p = Width of pavement contributing to gutter flow, m

E = Constant equal to 1 for first inlet in all cases and equal to capture efficiency for subsequent inlets on constant slope bridges

Notes: 1. *For constant slope, E = 1; $L_O = L_C$ for first inlet; $L_C = L_C$, for others.*

2. *For vertical curve, E = K; K = 1, $L_O = L_C$ for the first inlet; $L_O = L_C$, for others.*

4. Step 4. Compare L_C with the length of the bridge. If L_C is greater than the length of the bridge, inlets are not needed and only bridge end treatment is needed. If L_C is less than the bridge length, go to Step 5.

5. Step 5. If inlets are required, the designer should calculate the constant inlet spacing, L_C, for the subsequent inlets. In order to do this, it will be necessary to determine the capture efficiency, E, for the type of inlet that is proposed for use. *Note: For Type SQ inlets where the grate is transverse to the direction of travel for bicycles, a reduction in capture efficiency will be required as indicated in* Figure 33-5C.

   For circular drains, such as the slab bridge floor drain, Figure 33-5A, Efficiency Curves for Circular Drains, summarizes results from a laboratory study. To use the figure, calculate the ratio of inlet diameter, D, to gutter spread, and enter the graph at the appropriate value along the x-axis. Upon interception with the applicable curve (or appropriate interpolated curve), read efficiency, E, from the y-axis.

   For rectangular inlets, several steps are necessary to calculate flow interception efficiency, E, which is the ratio of intercepted to total deck flow.

   a. Find the ratio of frontal flow, E_O, bound by the width of grate, W, to total deck flow, using Figure 33-5B, Ratio of Frontal Flow to Total Gutter Flow (Rectangular Inlets), or:

   $$E_O = 1 - (1 - W/T)^{2.67} \qquad \text{(Equation 33-5.2)}$$

   b. Find the flow intercepted by the inlet as a percent of the frontal flow. The gutter velocity is needed and is provided by Equation 33-4.2.

   c. Identify the grate type and, using Figure 33-5C, Grate Inlet Frontal Flow Interception Efficiency, determine the portion of frontal flow (R_f, the total flow within a grate width from the curb) that is intercepted by a grate. This will be less than 100% when the gutter velocity exceeds the splashover velocity.

d. The interception efficiency, E, is then computed as:

$$E = R_f E_O \qquad \text{(Equation 33-5.3)}$$

If the designer wishes to consider side flow, refer to Chapter Thirty-six.

e. The flow intercepted by an inlet is:

$$Q_i = EQ_w \quad \text{where: } Q_w = E_O Q \qquad \text{(Equation 33-5.4)}$$

f. The flow bypassing an inlet is:

$$Q_b = Q\left[E_O(1 - E) + (1 - E_O)\right] \qquad \text{(Equation 33-5.5)}$$

6. Step 6. After E is determined, solve for L_C, spacing of all inlets using Equation 33-5.1. Because bridge deck grade and time of concentration are assumed to be constant, the spacing between inlets will be constant.

7. Step 7. Continue to space inlets until the end of the bridge is reached. Once L_O and L_C have been determined analytically, these values may need to be adapted to accommodate structural and aesthetic constraints.

33-5.01(02) Example Problem 33-5.1

Given: Two-Lane Urban Arterial
120-m bridge with 0.5% grade (S_O = 0.005)
40 deg 0 min Latitude and 86 deg 0 min Longitude
W_p = 6 m (from the centerline crown to the gutter edge)
C = 0.9
T = 2.4-m shoulder + 1.2 m allowable encroachment = 3.6 m
n = 0.016
S_X = 0.02
10-year return period

Inlets, if provided, will be Grate A on Roadway Design Type SQ. The bridge has a waterproof expansion joint. All upslope pavement drainage is intercepted by bridge end collectors.

Find: Inlet spacing, L_O, L_C.

Solution: Use the Procedure for constant-grade bridges.

1. Step 1. Compute intensity, i, for time of concentration, t_C, to first inlet. Figure 33-5D, IDF Data from HYDRO (40 deg Latitude and 86 deg Longitude), reproduces the IDF data from HYDRO for the given latitude and longitude for the 10-year return period. Use the IDF data and the time of concentration equations in Section 33-3.0 in the iterative process.

   a. Select a trial value for t_C of 10 min and verify this assumption.

   b. From the IDF data, i_{10} for 10 min in duration is 136 mm/h.

   c. Compute the overland flow time of concentration using Equation 33-3.2:

$$t_O = 6.92 \frac{(6)^{0.6}\,(0.016)^{0.6}}{\left[[(0.9)(136)]^{0.4}\,(0.02)^{0.3}\right]} = 0.80 \text{ minutes}$$

   d. Compute gutter flow time of concentration using Equation 33-3.3. Because the upslope bridge end inlet intercepts all approach flow, E = 1:

$$t_g = 40\,333 \frac{(0.02)\,(3.6)^2}{(0.9)(136)(6)} = 14.2 \text{ minutes}$$

   e. Compute total t_C and compare with selected value:

$$t_C = 0.80 + 14.2 = 15.0 \text{ minutes}$$

   f. Because the trial value of 10 min and the computed value of 15 min are not equal, select another trial t_C value of 19 min and repeat steps (c) through (e). The interpolated value of i from Figure 33-5D, IDF Data from HYDRO (40 deg Latitude and 86 deg Longitude), for a duration of 19 min is 105 mm/h.

   g. The computed time of concentration for the second trial duration is 19.02 min, which is very close to 19.0 min. Therefore, use i = 105 mm/h as the design rainfall intensity.

2. Step 2. Compute full gutter flow based on the design spread of 3.6 m. Use Equation 33-4.1:

$$Q_f = \left(\frac{0.38}{0.016}\right)(0.02)^{1.67}\,(0.005)^{0.5}\,(3.6)^{2.67} = 0.075 \text{ m}^3/\text{s}$$

3. Step 3. Starting at the upslope end of the bridge, compute the distance to the first inlet, L_O, using Equation 33-5.1 with E = 1:

$$L_O = \frac{(3.63 \times 10^6)(0.075)}{(0.9)(105)(6)} = 480 \text{ m}$$

4. Step 4. Compare L_O = 480 m with the bridge length of 120 m . Because L_O is greater than the total bridge length (120 m), drainage inlets are not required on the bridge.

5. Step 5. Not applicable.

6. Step 6. Not applicable.

7. Step 7. Not applicable.

33-5.01(03) Example Problem 33-5.2

Given: 6-lane Rural Freeway
675-m bridge on 1% grade (S_O = 0.01)
40 deg 0 min Latitude and 86 deg 0 min Longitude
W_P = 10.2 m (from the centerline crown to the gutter edge)
n = 0.016
C = 0.9
S_X = 0.02
T = 3 m (to edge of traveled way)
10-year return period

Bicycle traffic is not allowed on the bridge; therefore, inlets will be Grate A on Type SQ Casting, 480-mm square.

The bridge has waterproof expansion joint. All upslope pavement drainage is intercepted by bridge end collector.

Find: Inlet spacing, L_O, L_C.

Solution: Use the Procedure for constant-grade bridges:

1. Step 1. Compute intensity, i, for time of concentration, t_c, to the first inlet. Use the IDF data in Figure 33-5E, Parameters for Equation 33-5.6, and the time of concentration equations in Section 33-3.0 in an iterative procedure:

   a. Select trial value for t_C of 6 minutes and verify the assumption.

   b. The i for duration of 6 minutes is 162 mm/hr from IDF data.

   c. Compute overland flow time of concentration using Equation 33-3.2:

$$t_O = 6.92 \frac{(10.2)^{0.6}(0.016)^{0.6}}{[(0.9)(162)]^{0.4}(0.02)^{0.3}} = 1.03 \text{ minutes}$$

   d. Compute gutter flow time of concentration using Equation 33-3.3. Because the upslope bridge end inlet intercepts all approach flow, E = 1:

$$t_g = 40\,333 \frac{(0.02)(3)^2}{(0.9)(162)(10.2)} = 4.88 \text{ minutes}$$

   e. Compute total t_C and compare with selected trial value:

$$t_C = 1.03 + 4.88 = 5.91 \text{ minutes}$$

   f. Because the trial value and the computed value are approximately equal, use i = 162 mm/hr as design rainfall intensity.

2. Step 2. Compute full gutter flow for the design spread of 3 m. Use Equation 33-4.1:

$$Q_f = \left(\frac{0.38}{0.016}\right)(0.02)^{1.67}(0.01)^{0.5}(3)^{2.67} = 0.065 \text{ m}^3/\text{s}$$

3. Step 3. Starting at the upslope end of the bridge, compute the distance to the first inlet, L_o, using Equation 33-5.1:

$$L_O = \frac{(3.63 \text{ x } 10^6)(0.065)(1)}{(0.9)(162)(10.2)} = 158 \text{ m}$$

4. Step 4. Because L_O (158 m) is less than the total bridge length (675 m), inlets are needed.

5. Step 5. Determine the inlet efficiency, E, for the rectangular inlets:

   a. Using Equation 33-5.2, compute the frontal flow ratio, E_O:

$$E_O = 1 - \left(1 - \frac{0.480}{3}\right)^{2.67} = 0.37$$

b. Using Equation 33-4.2, compute gutter velocity:

$$V = \frac{(2)(0.38)}{0.016}(0.01)^{0.5}(0.02)^{0.67}(3)^{0.67} = 0.72 \text{ m/s}$$

c. Using Figure 33-5C, find the frontal flow intercept efficiency, R_f, for a parallel bar grate, L = 0.480 m. The splashover velocity is approximately 1.3 m/sec, which is greater than the gutter velocity which implies an R_f = 1.0.

d. Therefore, the interception efficiency from Equation 33-5.3 is:

$$E = (0.37)(1) = 0.37$$

6. Step 6. Compute constant spacing for the remainder of the inlets using Equation 33-5.1:

$$L_C = \frac{(3.63 \text{ x } 10^6)(0.065)}{(0.9)(162)(10.2)}(0.37) = 58 \text{ m}$$

7. Step 7. Adapt spacing to structural constraints. For example, if bent spacing is 55 m to 60 m, place the first inlet at the second bent approximately 110 m to 120 m from the high end of the bridge. Place an inlet at each bent thereafter for a total of 10 or 11 inlets, depending on the bent spacing.

33-5.02 Flat Bridges

33-5.02(01) Procedure

Bridges with vertical curves, having either sags or crests, are nearly flat at their low- or high-point stations. Bridges with grades less than about 0.3 percent are nearly flat. For nearly flat stations on vertical curve bridges or bridges with constant grades, the designer should check spacing assuming the bridge is flat. If the flat spacing is less than the spacing determined using a nearly flat grade, then the provision of the flat grade spacing is warranted. Use the following procedure.

1. Step 1. The time of concentration (t_C) to each inlet is assumed to be 5 minutes. Frequency, design spread (T), pavement width (W_P), bridge length (L_B), Manning's n (n), Rational runoff coefficient (C) and gutter slope (S_X) are assumed to be known. Using a

time of concentration of 5 minutes and the selected frequency, rainfall intensity is determined from HYDRO or from the regional IDF curves in Chapter Twenty-nine.

2. Step 2. Constant inlet spacing, L_C, can then be computed using Equation 33-5.6:

$$L_c = \left[\frac{19\,330}{(nCi\,W_P)^{0.67}} \right] S_x^{1.44}\ T^{2.11} \qquad \text{(Equation 33-5.6)}$$

Where: Variables as previously defined. Figure 33-5E illustrates the parameters for Equation 33-5.6.

3. Step 3. Compare the computed spacing with the known bridge length. If L_C is greater than the length of the bridge, then there is no need for inlets and the designer need only be concerned with the design of bridge end treatments (Step 6). If L_C is less than the bridge length, then the total needed inlet perimeter (P) can be computed using Equation 33-5.7, which is based on critical depth along the perimeter of the inlet (weir flow):

$$P = \frac{(CiW_p)^{0.33}\,T^{0.61}}{320\,S_x^{0.06}\,n^{0.67}} \qquad \text{(Equation 33-5.7)}$$

Where: Variables as previously defined. Figure 33-5F illustrates the parameters for Equation 33-5.7.

4. Step 4. Select inlet based on perimeter requirements.

5. Step 5. Adapt spacing to accommodate structural and aesthetic constraints.

33-5.02(02) Example Problem 33-5.3

Given:
6-lane rural freeway
300-m bridge
40 deg 0 min Latitude and 86 deg 0 min Longitude
W_P = 10.2 m (from centerline crown to the gutter edge)
n = 0.016
C = 0.9
S_X = 0.02
T = 3 m (to edge of traveled way)
10-year return period

Find: Inlet spacing, L_C, and total inlet perimeter, P.

Solution: Use the Procedure for flat bridges:

1. Step 1. Compute intensity for time of concentration of 5 minutes from the IDF data in Figure 33-5D; i = 168 mm/hr.

2. Step 2. Compute inlet spacing, L_C, using Equation 33-5.6:

$$L_c = \left[\frac{19\,330}{[(0.016)(0.9)(168)(10.2)]^{0.67}} \right] (0.02)^{1.44} (3)^{2.11} = 82 \text{ m}$$

3. Step 3. Because $L_C < 300$ m (the length of the bridge), inlets are needed. Compute total inlet perimeter using Equation 33-5.7:

$$P = \frac{[(0.9)(168)(10.2)]^{0.33} (3)^{0.61}}{320(0.02)^{0.06} (0.016)^{0.67}} = 1.39 \text{ m}$$

4. Step 4. Any inlet configuration may be used if the total inlet perimeter is at least 1390 mm. If the square or rectangular grate is adjacent to the curb, then the sum of the other three sides should be 1390 mm. Thus, 1390 / 3 = 463 mm. Either drain type OS or SQ would be adequate. Round floor drains, such as the slab bridge floor drain, could be used. In this case, three 150-mm diameter drains would be necessary at 80-m intervals or 1 drain at 25-m intervals.

5. Step 5. Adapt spacing and type of inlet to structural constraints.

33-5.03 Vertical Curve Bridges

33-5.03(01) Procedure

The methodology for spacing inlets on vertical curve bridges is similar to that for constant grade bridges except that a trial-and-error approach is incorporated into the inlet spacing computations to reflect the estimated grade at the next inlet. The designer first selects a design frequency and design spread. General bridge dimensions, bridge end grades, roughness and runoff coefficients and inlet specifications are assumed to be given. Using basic geometry, the designer computes the distance from the high point to each end of the bridge (L_{E1}, L_{E2}). Use the following procedure.

1. Step 1. Compute the lengths of the short and long ends of the bridge, L_{E1}, L_{E2}, by solving Equation 33-5.8:

$$S = \left(\frac{g_2 - g_1}{L_B} \right) X + g_1 \qquad \text{(Equation 33-5.8)}$$

Where: L_B = length of bridge, m
g_1,g_2 = slopes of the tangents of the vertical curve, decimals

Solving for X with S = 0 provides the distance from the left edge to the high point (L_{E1}).

2. Step 2. Determine the rainfall intensity based on the computed time of concentration to the first inlet as follows:

   a. Select trial time of concentration and determine rainfall intensity from the IDF data.

   b. Compute overland travel time, t_O, using Equation 33-3.2.

   c. Compute gutter travel time, t_g, using Equation 33-3.3.

   d. Compute time of concentration by summing the gutter and overland travel times.

   e. Compare computed time with trial time in a. and repeat if necessary.

3. Step 3. Select a trial distance from the high point to the first inlet on the long end of bridge, L_O, and compute the local slope using Equation 33-5.8.

4. Step 4. Compute gutter flow, Q_f, corresponding to the design spread using Equation 33-4.1.

5. Step 5. Compute the distance to the first inlet, L_O, letting K = 1 for the first inlet, and using Equation 33-5.1. (Substitute K for E and L_O for L_C in the equation.)

6. Step 6. Determine spacing to the next inlet on the long end of the bridge as follows:

   a. Select a trial L_1.

   b. Compute the local slope, S, using Equation 33-5.30.

   c. Calculate the gutter flow, Q, using Equation 33-4.1.

d. Compute inlet efficiency, E, using Figure 33-5A for circular scuppers and Figure 33-5B, Equation 33-4.2, Figure 33-5C and Equation 33-5.3 for rectangular inlets.

e. Compute the interception, K, (K is less than 1 for inlets following the first), using Equation 33-5.9:

$$K = 1 - (1 - E)\left[\frac{S_u}{S}\right]^{0.5} \qquad \text{(Equation 33-5.9)}$$

Where: $E = E_O R_f$ = Interception efficiency
S_U = Longitudinal grade for upstream inlet on vertical curve bridge.

f. Compute inlet spacing, L_1, using Equation 33-5.1 (substitute K for E and L_1 for L_C in the equation), and compare to the trial L_1 in Step 6a. If the computed L_1 does not equal the trial L_1 value, repeat Step 6.

7. Step 7. Repeat Step 6 for the next inlet. Inlet spacings are determined one at a time until the sum of the inlet spacings exceeds the length of the long side of the bridge. Spacings on the short side of the bridge (starting from the high point and working down) will be the same as those determined for the long side until, of course, the length of the short side is exceeded. The spacing of the vertical curve deck inlets are symmetrical with respect to the high point of the bridge.

8. Step 8. Adapt spacing of inlets to accommodate structural constraints.

33-5.03(02) Example Problem 33-5.4

Given: 6-lane rural freeway
Bridge with vertical curve
40 deg 0 min Latitude and 86 deg 0 min Longitude
W_P = 10.2 m (from centerline crown to gutter edge)
n = 0.016
S_X = 0.02
T = 3 m (to edge of traveled way)
C = 0.9
L_B = 600 m
10-year return period
g_1 = +0.01
g_2 = -0.02

Inlets will be Type SQ, 480-mm square. Bicycle traffic is not allowed.

Find: Inlet spacing L_O, L_1, L_2, L_3, etc.

Solution: Use the Procedure for vertical curve bridges:

1. Step 1. Compute L_{E1} and L_{E2}, assuming a parabolic vertical curve. Locate high point, X_{HP}, using Equation 33-5.30 with S = 0:

$$X_{HP} = (-0.01)\left[\frac{(600)}{(-0.02 - 0.01)}\right] = 200 \text{ m}$$

Thus: L_{E1} = 200 m and L_{E2} = 600 - 200 = 400 m

2. Step 2. Compute intensity for time of concentration to first inlet. Use IDF data in Figure 33-5D:

   a. Select trial time of concentration of 6 minutes. Then i_{10} = 162 mm/hr for 10-year return period.

   b. Compute t_O from Equation 33-3.2:

$$t_O = 6.92 \frac{[(10.2)\,(0.016)\,]^{0.6}}{[(0.9)(162)\,]^{0.4}\,(0.02\,)^{0.3}} = 1.03 \text{ minutes}$$

   c. Compute t_g from Equation 33-3.3:

$$t_g = 40\,333 \frac{(0.02)\,(3)^2}{(0.9)(162)(10.2)} = 4.88 \text{ minutes}$$

   d. Compute t_C:

$$t_C = 1.03 + 4.88 = 5.91 \text{ minutes}$$

   e. The calculated t_C is sufficiently close to the assumed t_C. Therefore, use 162 mm/hr as the design rainfall intensity.

3. Step 3. Select a trial value for the distance from the bridge high point to the first inlet (working down the long side of the bridge) and compute the local slope.

   a. Select L_O = 100 m (1st trial)

$$S = \frac{(-0.02 - 0.01)}{600}(300) + 0.01 = -0.005$$

$X = 200 + 100 = 300$ m (distance from the left end)

(Use $|S| = 0.005$)

b. Use Equation 33-5.8 to determine S:

4. Step 4. Compute full gutter flow, Q_f, at design spread (3 m) for Equation 33-4.1:

$$Q_f = \left(\frac{0.38}{0.016}\right)(0.02)^{1.67}(0.005)^{0.5}(3)^{2.67} = 0.046\ m^3/s$$

5. Step 5. Compute distance to first inlet, L_O, (K = 1 for first inlet) using Equation 33-5.1:

$$L_O = \frac{(3.63 \times 10^6)(0.046)}{(0.9)(162)(10.2)} = 112\ m$$

Use $L_O = 100$ m. Inlets are needed because L_O is less than the length of the long side of the bridge.

6. Step 6. Determine spacing to next inlet as follows:

a. Select $L_1 = 30$ m (1st trial).

$X = 200 + 100 + 30 = 330$ m (distance from left end)

b. Use Equation 33-5.30 to determine S:

$$S = \frac{(-0.02 - 0.01)}{600}(330) + 0.01 = -0.0065 \qquad \text{(Use } |S| = 0.0065\text{)}$$

Note: S_U = prior S = 0.0050 (slope at immediately upstream inlet).

c. Compute full gutter flow, Q_f, using Equation 33-4.1:

$$Q_f = \left(\frac{0.38}{0.016}\right)(0.02)^{1.67}(0.0065)^{0.5}(3)^{2.67} = 0.052\ m^3/s$$

d. Compute inlet efficiency, E, for rectangular inlets using Equation 33-5.2 or Figure 33-5B.

$$E_O = 1 - [1 - 0.48/3]^{2.67} = 0.37$$

$$V = \left(\frac{0.76}{0.016}\right)(0.02)^{0.67}(0.0065)^{0.5}(3)^{0.67} = 0.58\ m/s$$

$R_f = 1.0$ (Figure 33-5C, Grate Inlet Frontal Flow Interception Efficiency)

$E = E_O R_f = 0.37 (1.0) = 0.37$

Note: From Figure 33-5C, splashover does not occur for parallel grates until a gutter velocity of 1.3 m/s is reached corresponding to a slope of 1.9%. Thus, R_f will equal 1.0 and E will equal 0.37 for the remainder of this example. For less efficient grates on steep slopes, E can change from inlet to inlet.

e. Compute interception coefficient, K, using Equation 33-5.9 (K does not equal 1 for the second inlet):

$K = 1 - (1 - 0.37) [0.005/0.0065]^{0.5} = 0.45$

f. Compute inlet spacing, L_1, using Equation 33-5.1:

$$L_1 = \frac{(3.63\,x10^6)(0.052)}{(0.9)(162)(10.2)}(0.45) = 57.1 \text{ m (not equal to 30 m as assumed)}$$

7. Repeat Step 6. Because the computed value for L_1 does not equal the trial value, select a new trial value for L_1 and repeat Step 6:

a. Select $L_1 = 75$ m (2nd trial).

$X = 200 + 100 + 75 = 375$ m (Equation 33-5.10)

b. Use Equation 33-5.8 to redetermine S:

$$S = \frac{(-0.02 - 0.01)}{600}(375) + 0.01 = -0.00875 \text{ (use } |S| = 0.00875)$$

Note: S_U still = 0.005

c. Recompute Q:

$$Q = \left(\frac{0.38}{0.016}\right)(0.02)^{1.67}(0.00875)^{0.5}(3)^{2.67} = 0.061 \text{ m}^3/\text{s} \quad \text{(Equation 33-5.11)}$$

d. Recompute inlet efficiency, E:

$E = 0.37$ (no change as noted) (Equation 33-5.12)

e. Recompute interception coefficient, K_1:

$$K = 1 - (1 - 0.37)[0.005/0.00875]^{0.5} = 0.524 \qquad \text{(Equation 33-5.13)}$$

f. Recompute inlet spacing, L_1:

$$L_1 = \frac{(3.63x10^6)(0.061)}{(0.9)(162)(10.2)}(0.524) = 78 \text{ m} \qquad \text{(Equation 33-5.14)}$$

This is sufficiently close to 75 m.

8. Step 7. Determine spacing to next and subsequent inlets. Select the values as follows:

L_2 = 75 m
X = 450 m
S = 0.0125
Q = 0.073 m^3/s
E = 0.37
K_1 = 0.473
L_2 = 84 m OK

Inlet Spacing From High Point			**Slope, S**	**Gutter Flow, Q (m^3/s)**
L_i	**Long Side**	**Short Side**		
L_O	100 m	100 m	0.0050	0.046
L_1	75 m	75 m	0.00875	0.061
L_2	75 m	N/A	0.0125	0.073
L_3	75 m	N/A	0.0163	0.083

9. Step 8. Adapt spacings to accommodate structural constraints.